Int J Life Cycle Assess (2009) 14:411–419
DOI 10.1007/s11367-009-0095-3

CASE STUDY • INTEGRATED MUNICIPAL SOLID WASTE MANAGEMENT SYSTEM

Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems

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Received: 3 April 2009 / Accepted: 10 May 2009 / Published online: 4 June 2009

Abstract
Background, aim, and scope Life cycle assessment (LCA) applied to alternative waste management strategies is becoming a commonly utilised tool for decision makers. This LCA study analyses together material and energy recovery within integrated municipal solid waste (MSW) management systems, i.e. the recovery of materials separated with the source-separated collection of MSW and the energy recovery from the residual waste. The final aim is to assess the energetic and environmental performance of the entire MSW management system and, in particular, to evaluate the influence of different assumptions about recycling on the LCA results.
Materials and methods The analysis uses the method of LCA and, thus, takes into account that any recycling activity influences the environment not only by consuming resources and releasing emissions and waste streams but also by replacing conventional products from primary production. Different assumptions about the selection efficiencies of the collected materials and about the quantity of virgin material substituted by the reprocessed material were made. Moreover, the analysis considers that the energy recovered from the residual waste displaces the same quantity of energy produced in conventional power plants and boilers fuelled with fossil fuels.
Results The analysis shows, in the expanded model of the material and energy recovering chain, that the environmental gains are higher than the environmental impacts. However, when we reduce the selection efficiencies by 15%, the impact indicators worsen by a percentage included between 10% and 26%. This phenomenon is even more evident when we consider a substitution ratio of 1:<1 for paper and plastic: The worsening is around 15–20% for all the impact indicators except for the global warming for which the worsening is up to 45%.
Discussion Hypotheses about the selection efficiencies of the source-separated collected materials and about the substitution ratio have a great influence on the LCA results. Consequently, policy makers have to be aware of the fact that the impacts of an integrated MSW management system are highly dependent on the assumptions made in the modelling of the material recovery, as well as in the modelling of the energy recovery.
Conclusions LCA allows to evaluate the impacts of integrated systems and how these impacts change when the assumptions made during the modelling of the different single parts of the system are modified. Due to the significant impacts that hypotheses about material recovery have in the results, they should be expressed in a very transparent way in the report of LCA studies, together with the assumptions made about energy recovery.
Recommendations and perspectives The results suggest that the hypotheses about the value of the substitution ratio are very important, and the case of wood should therefore be better analysed and a substitution ratio of 1:<1 should be used, as for paper and plastic. It seems that the assumptions made about which material is replaced by the recycled one are very important too, and in this sense, more research is needed about what the recycled plastic may effectively substitute, in particular the polyolefin mix.

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Keywords Integrated waste management systems · Life cycle assessment · Recycling · Selection efficiencies · Substitution ratio

1 Background, aim and scope

Life cycle assessment (LCA), originally developed for assessing environmental impacts of products, processes and activities with the so-called cradle to grave approach has, in the last few years, evolved towards extended applications related to a broader range of human activities involving environmental interactions, as waste management, treatment and disposal operations. LCA applied to alternative waste management strategies is becoming a commonly utilised tool for decision makers (Finnveden 1999), but only a few studies analysed municipal solid waste (MSW) management from a systems perspective (AEA 2001; Eriksson et al. 2005; Heilmann and Winkler 2005; Profu 2004; Thorneloe et al. 2005). The main conclusion of all these studies is that reduced landfilling in favour of increased recovery of energy and materials leads to lower environmental impact and lower consumption of energy resources.

This LCA study analyses material and energy recovery within an integrated MSW management system from an energetic and environmental point of view. The recovery of materials separated with the source-separated collection of MSW, i.e. the recycling of iron, aluminium, glass, paper, wood and plastic and the composting of food and green waste, is analysed together with the energy recovery from the residual waste, i.e. the incineration with energy recovery. In particular, this research evaluates how different assumptions about recycling influence the LCA results of the studied integrated waste management system. The influence of assumptions on energy recovery has already been analysed by a lot of studies (e.g. Sonesson et al. 2000; AEA 2001; Profu 2004; Björklund and Finnveden 2005; Consonni et al. 2005a, b; Eriksson et al. 2005; Finnveden et al. 2005; Moberg et al. 2005; Thorneloe et al. 2005), which concluded that the energy efficiency of the plant and the assumed "substituted energy" are the most important factors able to significantly modify the LCA results.

2 Materials and methods

2.1 Methodology and impact indicators

The analysis uses the technique of LCA (Rebitzer et al. 2004, Pennington et al. 2004) following ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards. It takes into account that any recycling activity influences the environment by consuming resources and releasing emissions and waste streams and by replacing conventional products from primary production. Moreover, the energy recovered from the residual waste displaces the same quantity of energy produced in conventional power plants and boilers fuelled with fossil fuels.

The Simapro 7 software, developed by PRè Consultants (2006), is used for the evaluation of the energetic and environmental impacts of the various processing steps. Two characterisation methods are used: the Cumulative Energy Demand (Jungbluth and Frischknecht 2004), in order to calculate the total energy demand (CED), and the CML 2001 (CML et al. 2001), in order to evaluate the environmental impacts. In this second method, properly adapted according to Rigamonti (2007), the following impact categories have been selected:

- Global warming potential (GWP), which accounts for the emission of greenhouse gases.
- Human toxicity potential (HTP), which includes a wide range of toxic substances: In this study, we have added the impact of the secondary fine particulate in order to better take into account the atmospheric situation of the North of Italy (Lonati et al. 2008).
- Acidification potential (AP), which accounts for the emissions of NO_x, SO_x and ammonia.
- Photochemical ozone creation potential (POCP), which accounts for the substances that cause the photochemical ozone production in the troposphere: In this study, we have eliminated the distinction between NO and NO_2, and we have added NO_x (as NO_2) because, in most of the processes, the emission factor is given as NO_x, and it is not always straightforward to split it properly. Moreover, we have added the characterisation factor for NMCOV as a whole.

2.2 The MSW management system analysed

The integrated MSW management system considered in this study to assess how the assumptions about selection and recycling efficiencies influence LCA results of the whole system is characterised by a source-separated collection of about 50%. This scenario is a theoretical one, but it is consistent with mid-term regional targets in Italy. The fractions collected separately are sent to material recovery processes, whereas the residual waste is sent to energy recovery. Material recovery includes the recycling of packaging materials (iron, aluminium, glass, paper, wood and plastic) and the composting of food and green waste.

Table 1 reports the MSW composition before any collection: It was calculated based on a number of analyses and represents the Italian average (Rigamonti

Table 1 MSW composition before any collection (Rigamonti 2007) and quantity collected for each fraction, expressed in percentage and in kilogram per 1 tonne of gross MSW produced (Rigamonti et al. 2008a)

Fractions	MSW composition before any collection (%)	Source-separated collection (%)	Source-separated collection (kg t_{MSW}^{-1})
Paper	25.8	74	191
Wood	4.6	35	16
Plastic	14.6	30	44
Glass and inert material	5.8	70.5	41
Metals without Al	2.1	61	13
Aluminium	0.6	19	1
Food waste	22.9	50	115
Green waste	8.6	60	52
Fines	11.9	0	0
Other	3.1	100	31
Total	100	50.3	503

2007). Source-separated collection efficiencies (see Table 1) were found in literature and refer to Italian experiences (Rigamonti et al. 2008a).

2.3 LCA of material recovery: inventory and assumptions

2.3.1 Data for material recovery

Data about emissions, energy consumptions and material flows have been gathered for both the production starting from waste materials (i.e. secondary production) and the production starting from virgin raw materials (i.e. primary or virgin production). While the latter are available from the literature (IPPC 2001a, b, c; Fruhwald and Hasch 1999) and from international databases (e.g. ecoinvent—Swiss Centre for Life Cycle Inventories 2007), the former were acquired mainly from direct contacts with the operators of the most important recycling and composting plants located in the North of Italy. A brief description of the most relevant aspects of packaging materials recycling and food and green waste composting useful for this study can be found in Grosso et al. (2007) and Rigamonti et al. (2008b).

In particular, using data from Italian selection plants, we have supposed that selected plastic is composed by 55% of polyethylene terephthalate (PET), 20% of high-density polyethylene (HDPE) and 25% of a mix composed by 57% of low-density polyethylene (LDPE), 35% of linear low-density polyethylene (LLDPE) and 8% of polypropylene (PP). Each polymer is mechanically recycled to obtain granules of the recycled polymers (R-PET, R-HDPE and R-mix). The recovery efficiencies considered are respectively 75.5% for PET, 90% for HDPE and 60% for the mix (data gathered from a state-of-the-art Italian recycling plant).

Collected wood is supposed to be used in the production of particle boards, whereas collected paper is used in the production of secondary pulp without any bleaching or deinking treatment. Aluminium scrap is used in the production of ingots, steel scrap in the production of liquid recycled steel and glass cullet in the production of packaging green glass. Food and green wastes are sent to a composting plant.

There are two different phases involved in the recycling of packaging materials: the selection and the reprocessing. We have supposed that each collected packaging material is transported to a selection plant, located at a distance of 40 km from the collection centre. In the plant, the materials are cleaned from the contaminant. The selected material is then transported to the reprocessing plant (transport distance, 200 km). Food and green wastes are transported to a composting plant (transport distance, 40 km) where they undergo aerobic biological treatment and refining.

Table 2 reports, for selection and reprocessing phases, the data about material flows involved both in packaging materials recycling and food and green waste composting. Selection efficiencies reported in Table 2 refer to a mono-material collection conducted by a mix between on street banks systems and kerbside systems and are representative of a well-structured collection system. They are an average between values obtained directly by some operators of Italian selection plants and values found in literature (CNA 2006; CiAl 2005, personal communication; COREVE 2005; AmbienteItalia—Comieco 2003; Arianna 2000; CITEC 2004). Selection efficiencies are subjected to a great variability because they are influenced by the type of collection (on street banks system vs. kerbside system and mono-material collection vs. multi-material collection), the level of collection and by the civil behaviour of citizens. To take into account this variability, we have also used a second set of data in the LCA, where selection efficiencies of packaging materials are those reported in Table 2 reduced by 15% (for example, in the case of plastic, the selection efficiency changes from 75% to 60%).

Recovery efficiencies reported in Table 2 are an average between values obtained directly by the operators of the most important recycling and composting plants located in the North of Italy and values found in literature (IPPC 2001a; COREVE 2003; Arena et al. 2004; Comieco 2006; CITEC 2004).

2.3.2 What does the secondary material substitute?

With "secondary material", we mean the material produced by the recycling (e.g. aluminium from the melting of

Table 2 Recycling efficiencies, found from the combination of selection and reprocessing efficiencies, for the materials analysed

Material	Selection efficiency (% in weight), (*A*)	Reprocessing efficiency (% in weight), (*B*)	Recycling efficiency (% in weight), ($A \times B$)
Steel	90	90.5 (melting furnace)	81.45
Aluminium	95	83.5 (melting kiln)	79.325
Glass	90.1	100 (melting furnace)	90.1
Paper	96.75	89 (pulp production)	86.11
Wood	86.5	95 (particle boards production)	82.175
Plastic	74.75	74.525 (mechanical recycling)	55.71
Food and green wastes	80	37.5 (composting)	30

scraps), whereas with “primary material”, we intend to mean the material produced starting from virgin raw materials (e.g. aluminium from bauxite). Recycling, in fact, allows one to have new materials, and these secondary materials can be used in substitution of the correspondent primary material. In this sense, when conducting a life cycle assessment, we have to take into account that any recycling activity influences the environment by consuming resources and releasing emissions and waste streams, but, at the same time, by replacing conventional products from primary production.

ISO 14040 (ISO 2006a) states that “consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems”, where the term allocation is defined as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”. Several allocation procedures are applicable for reuse and recycling. Changes in the inherent properties of materials shall be taken into account. These allocation procedures can be addressed as follows (ISO 14044—ISO 2006b):

- “Closed-loop allocation procedures applied to closed-loop product systems. It also applies to open-loop product systems, where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) material”
- “An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties. The allocation procedures should use, as the basis for allocation: physical properties (e.g. mass), economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material), the number of subsequent uses of the recycled material (see ISO/TR 14049—ISO 2000).”

On the basis of these considerations, we have calculated the LCA for two different scenarios:

- a first scenario using a closed-loop allocation procedure (substitution ratio of 1:1)
- a second scenario using an open-loop allocation procedure (substitution ratio 1:<1)

Scenario using a closed-loop allocation procedure (substitution ratio of 1:1) In this scenario, we have considered a closed-loop allocation procedure making the hypothesis that no changes occur in the inherent properties of the recycled material. In this way, as previously explained, the need for allocation is avoided since the use of secondary material displaces the use of virgin material. We do not consider the possible degradation of the material during the recycling so that the fact that the quality of the secondary material may be worse than that of the primary material. This means that, in the case of the packaging materials, we have used a substitution ratio of 1:1, and, in particular, we have supposed that 1 kg of secondary packaging materials (aluminium, steel, glass, pulp from paper, plastic) replaces 1 kg of the corresponding primary material and 1 m^3 of particle boards (produced using collected wood) replaces 1 m^3 of plywood (produced using virgin wood).

In the case of the organic fractions (food and green waste), we have assumed that 34% of the produced compost is used in garden centres in substitution of peat, 62% in agriculture in substitution of mineral fertilisers with the same content of nutrients (N, P and K) and 4% in environmental restorations without any substitution (Centemero 2006).

Scenario using an open-loop allocation procedure (substitution ratio of 1:<1) The substitution ratio of 1:1 is correctly applied only when no changes occur in the inherent properties of the recycled material. This is effectively true, for example, for aluminium and its alloys because, thanks to their metallic nature, they have the ability to maintain their inherent properties during recycling (European Aluminium 2007).

Table 3 Product obtained with the material recovery (secondary product) and corresponding substituted product (primary product) plus the substitution ratio used in the analysis

Material	Secondary product	Primary product	Substitution ratio
Iron	Liquid iron	Liquid iron	1:1
Aluminium	Aluminium ingot	Aluminium ingot	1:1
Glass	Generic glass container	Generic glass container	1:1
Wood	Particle board	Plywood	1:1
Paper	Pulp from recovered paper	Thermo-mechanical pulp	1:1 and 1:<1
Plastic	Granules of PET, HDPE, and mix of LDPE, LLDPE, PP	Granules of PET, HDPE, LDPE, LLDPE, PP	1:1 and 1:<1
Food and green waste	Compost	Peat and mineral fertilisers	–

If inherent properties are changed, like in recycled paper and plastic, the substitution ratio of 1:1 should not be applied.

Paper represents a specific case because, unlike aluminium, glass and iron, it can be recycled only a limited number of times, i.e. about five times (Comieco 2008). This means that virgin pulp (1 "entity") can be used in its entire life for producing only five secondary pulps (five "entities"). In this way, all the energy and material consumptions occurred in the production of virgin pulp are to be divided between six entities (and not infinite entities as in the case, for example, of aluminium). As a consequence, in the production of 1 kg of secondary pulp, we have added 1/6 of the energy and material consumptions occurring in the production of 1 kg of virgin pulp together with the energy and material consumptions for the recycling activity. With this assumption, 1 kg of secondary pulp plus 0.167 (1/6) kg of virgin pulp is assumed to substitute 1 kg of virgin pulp, i.e. 1 kg of secondary pulp replaces 0.833 (1–0.167) kg of virgin pulp. This means, in this case, that the substitution ratio is of 1:0.833. This value, calculated from the possible number of recycling cycles, as suggested in ISO/TR 14049, reflects the existing difference in mechanical properties and colour between the virgin pulp and the recycled pulp and thus allows one to take into account the quality loss of the material due to the recycle. Gentil et al. (2008) used a substitution ratio of 1:1 for cardboard fibres and of 1:0.9 for paper fibres and for plastic, whereas the European Topic Centre on Waste and Material Flows (2004) stated that the substitution ratio may well be around 1:1 for aluminium, but it is not higher than 1:0.8 for any paper or cardboard category.

In the case of plastics, the so-called value corrected substitution method can be used. This method is applied if there is a difference between the market value of the primary material and that of the corresponding recycled material. The method assumes that the substitution ability is reflected by the ratio between the market prices of the recycled and primary material (European Aluminium 2007). As an example, if the market price of the recycled material is 90% of the market price of the primary material, 1 kg of recycled material will substitute only 0.9 kg of primary material. The substitution between primary and recycled material should preferably be based on physical properties, but economic considerations can be used when information about characteristics and service durability of the recycled material in comparison to virgin material are not available, as what happens in this study. We have thus used this method for plastics, in a second calculation of the LCA: We know that film from virgin plastic costs €1.60 per kg, whereas film from secondary plastic costs €1.30 per kg (data for Italian situation as of 2008) so that 1 kg of recycled polymer will substitute only 0.81 kg of the corresponding primary polymer. The substitution ratio is

Table 4 Impact indicators for material recovery (expressed per 1 tonne of each source-separated material) when selection efficiencies of Table 2 are assumed and using a substitution ratio of 1:1

Per 1 source-separated tonne	Steel	Al	Glass	Paper	Wood	Plastic	Compost
CED (MJ eq.)	−11,210	−142,699	−6,426	−35,157	−20,019	−39,800	−205
GWP (kg CO_2 eq.)	−934	−9,216	−666	−625	−134	−1,082	−20
AP (kg SO_2 eq.)	−2.88	−59.8	−3.77	−3.23	−0.92	−3.75	0.115
HTP (kg 1,4-DCB eq.)	−103	−42,754	−156	−135	−87	−310	5.86
POCP (kg C_2H_4 eq.)	−0.21	−11.4	−0.213	−0.209	−0.261	−0.876	0.031

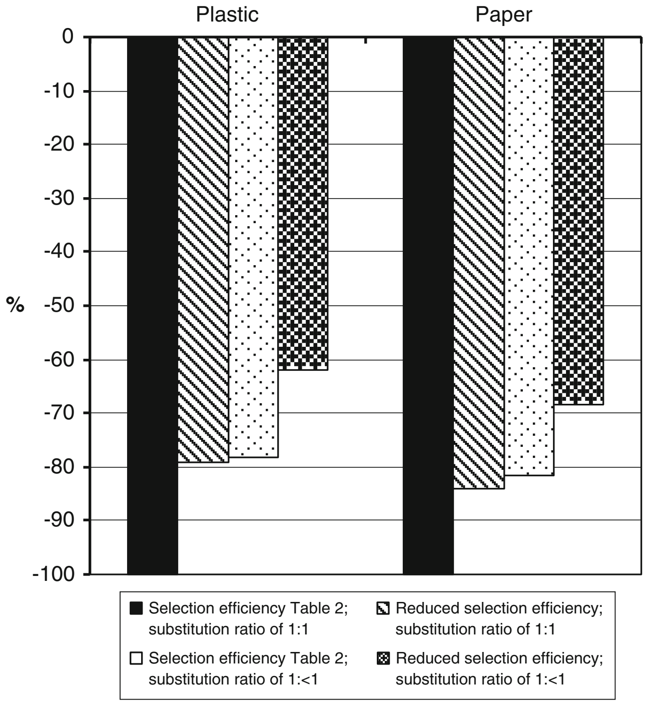

Fig. 1 Average decrease of impact indicators for plastic and paper recovery with the different assumptions made

therefore of 1:0.81. This value calculated from cost does not reflect the difference in mechanical properties only, but also in colour (in fact, recycled material cannot be freely coloured) and other side effects, like smell.

For the other packaging materials and for the organic fraction, we have used the same assumptions as in the previous scenario. Table 3 summarises for each material the product of the recovery and the corresponding substituted product with the substitution ratio used in the analysis.

2.4 Data for LCA of energy recovery

The residual waste is characterised by a lower heating value of 10,090 kJ/kg. It is sent to energy recovery in a waste-to-energy (WTE) plant.

We have considered a large plant, designed for a MSW management system of about 1,200,000 inhabitants, that produces electricity and heat. We have assumed that the amount of steam sent to district heating equals 30% of the total flow entering the steam turbine (yearly average): The plant net electrical efficiency is equal to 24.6%, while the net thermal efficiency is 19.2% (Consonni et al. 2006).

For the energetic and environmental balances, we have assumed that the electricity produced from the incinerator displaces the same quantity of electricity produced by the thermoelectric Italian grid in 2007, fuelled by coal for 18%, fuel oil for 10%, natural gas for 12% and natural gas in a combined cycle for 60% (Terna 2007, 2008). The heat produced displaces the same quantity of heat generated by household boilers fed with natural gas (thermal efficiency= 87%). A sensitivity analysis on this aspect was conducted in Rigamonti et al. (2008b).

3 Results

3.1 LCA results for material recovery

Table 4 reports the results of the LCA of material recovery when selection efficiencies of Table 2 are assumed and using the substitution ratio of 1:1 when considering what the secondary material substitutes.

Keeping in mind that a negative value indicates an advantage for the environment, whereas a positive value indicates a disadvantage, the main results show that recycling is energetically and environmentally convenient, especially for aluminium and plastic. The composting of food and green fractions appears to be neutral from an environmental point of view: the advantages in CED and GWP indicators, very limited in comparison with the packaging materials, are mostly associated with the substitution of peat.

If selection efficiencies of packaging materials reported in Table 2 are reduced by 15%, all the impact indicators show a worsening included between 16% (for aluminium) and 22% (for plastic). Moreover, the impact indicators for plastic, using the value corrected substitution method (substitution ratio of 1:<1), show a worsening of about 22% with the selection efficiency of 75% and of about 38%

Table 5 Impact indicators for plastic recovery (expressed per 1 tonne of source-separated plastic) for the different assumptions made

Per 1tonne of source-separated plastic	Selection efficiency 74.75; substitution ratio of 1:1	Selection efficiency 59.75; substitution ratio of 1:1	Selection efficiency 74.75; substitution ratio of 1:<1	Selection efficiency 59.75; substitution ratio of 1:<1
CED (MJ eq.)	−39,800	−31,685	−31,610	−25,131
GWP (kg CO_2 eq.)	−1,082	−855	−835	−657
AP (kg SO_2 eq.)	−3.75	−2.94	−2.87	−2.24
HTP (kg 1,4-DCB eq.)	−310	−246	−245	−195
POCP (kg C_2H_4 eq.)	−0.876	−0.694	−0.695	−0.55

Table 6 Impact indicators for paper recovery (expressed per 1 tonne of source-separated paper) for the different assumptions made

Per 1tonne of source-separated paper	Selection efficiency 96.75; substitution ratio of 1:1	Selection efficiency 81.75; substitution ratio of 1:1	Selection efficiency 96.75; substitution ratio of 1:<1	Selection efficiency 81.75; substitution ratio of 1:<1
CED (MJ eq.)	−35,157	−29,650	−29,156	−24,579
GWP (kg CO_2 eq.)	−625	−524	−513	−430
AP (kg SO_2 eq.)	−3.23	−2.71	−2.65	−2.22
HTP (kg 1,4-DCB eq.)	−135	−114	−108	−91
POCP (kg C_2H_4 eq.)	−0.209	−0.174	−0.169	−0.14

with the selection efficiency of 60% (Table 5 and Fig. 1). Considering the number of subsequent uses of the recycled paper (substitution ratio of 1:<1), the impact indicators for paper show a worsening of about 18% with the selection efficiency of 97% and of about 32% with the selection efficiency of 82% (Table 6 and Fig. 1).

3.2 LCA results for energy recovery

The results (Table 7) show that the incineration with energy recovery of the residual waste, in comparison with the production of the same amount of energy from fossil fuels, is environmentally convenient when the replaced electricity is produced from a mix of fossil fuels (10% oil, 18% coal, 12% natural gas and 60% natural gas used in a combined cycle), and the replaced heat is produced from natural gas. Table 7 shows how each impact indicator is split between the different contributions: the WTE plant (that includes the stack emissions, the residues treatments and the production of additives used in the flue gas treatment and of the materials used in the plant construction), the recycling of iron and aluminium recovered from the slag and the avoided energy thanks to the electricity and the heat produced by the plant.

3.3 LCA of the MSW integrated management system

Combining the results for material recovery with those for energy recovery, according to the quantities of each material reported in Table 1, allows the calculation of the LCA for the whole integrated MSW management system analysed.

Table 8 shows the results of the impact indicators when, in the material recovery, selection efficiencies of Table 2 are assumed and when the substitution ratio of 1:1 is used. All impact indicators have a negative value, which means that in the analysed expanded model of the material and energy recovering chain the energetic and environmental gains are higher than the energetic and environmental impacts.

When selection efficiencies of packaging materials reported in Table 2 are reduced by 15%, the impact indicators worsen by a percentage included between 10% and 26% (the last value being for the global warming indicator). This phenomenon is even more stressed when we consider the alternative allocation method for paper and plastic (substitution ratio of 1:<1): The reduction is around 15–20% for all the impact indicators except for the global warming one, for which the reduction is 45% (Fig. 2).

Table 7 LCA results for energy recovery: the different contributions to the total amount

Per t of residual waste	WTE plant	Material recovery (metals from slag)	Energy recovery (avoided thermoelectric mix and boiler)	Total
CED (MJ eq.)	1,084	−463	−9,288	−8,667
GWP (kg CO_2 eq.)	579	−33	−598	−52
AP (kg SO_2 eq.)	0.59	−0.16	−1.97	−1.54
HTP (kg 1,4-DCB eq.)	32	−79	−75	−122
POCP (kg C_2H_4 eq.)	0.064	−0.024	−0.178	−0.139

Table 8 Impact indicators of the integrated MSW management system when selection efficiencies of Table 2 are assumed and when the substitution ratio of 1:1 is used (expressed per 1 tonne of gross MSW produced)

Impact indicator	Value
CED (MJ eq./t_{MSW})	−13,700
GWP (kg CO_2 eq./t_{MSW})	−249
AP (kg SO_2 eq./t_{MSW})	−1.81
HTP (kg 1,4-DCB eq./t_{MSW})	−160
POCP (kg C_2H_4 eq./t_{MSW})	−0.172

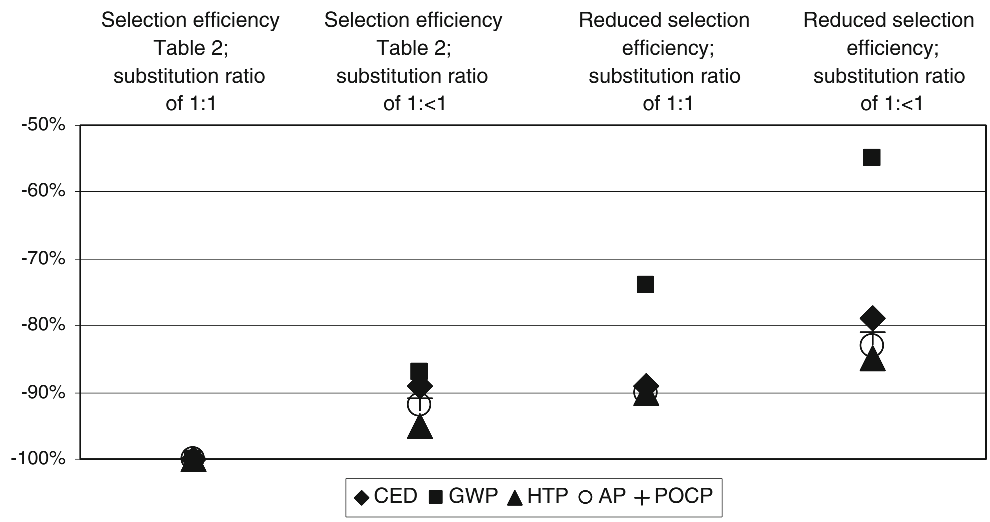

Fig. 2 Impact indicators of the integrated MSW management system modelled for the different cases analysed: For each indicator, that of the scenario performing best is set equal to −100% and those of the other scenarios are expressed as a percentage of it

4 Discussion

This LCA study analyses material and energy recovery within an integrated MSW management system. The recovery of materials (i.e. the recycling of iron, aluminium, glass, paper, wood and plastic and the composting of food and green fractions) and energy are considered together, with the final aim to evaluate the energetic and environmental performance of the entire MSW management system. In particular, this research analyses the influence of different assumptions about recycling on the LCA results of the whole MSW management system.

Hypotheses about the selection efficiencies of the source-separated collected materials have a great influence on the LCA results of the whole system: For example, reducing the selection efficiencies of 15% implies a worsening of the global warming indicator of 26%. The different substitution ratio has a great influence, too. Using a substitution ratio of 1:<1 based on the different economic value between virgin plastic and recycled plastic and based on the number of subsequent uses of paper recycled, instead of the substitution ratio of 1:1, together with the decrease of selection efficiencies, implies a worsening of the global warming indicator by 45%.

Consequently, the policy makers have to be aware of the fact that the impacts of an integrated MSW management system are highly dependent on the assumptions made in the modelling of the material recovery, as well as in the modelling of the energy recovery.

5 Conclusions

LCA is a powerful tool for assessing the environmental impacts of MSW management systems. In particular, it allows one to evaluate the impacts of integrated systems and how these impacts change in modifying the assumptions made during the modelling of the different single parts of the system.

This paper shows, in particular, the importance of the hypotheses made about material recovery, i.e. the selection efficiencies and the material quality loss during recycling. Due to the significant effects these assumptions have in the results, they should be expressed in a very transparent way in the report of LCA studies, together with those made about energy recovery.

6 Recommendation and perspectives

The results suggest that the hypotheses about the value of the substitution ratio are very important. It should thus be better analysed in the case of wood. In fact, also for wood, as for paper and plastic, recycling implies a material quality loss that should be accounted for in the LCA: in subsequent research, a correct substitution ratio should thus be found and used. It also seems that the assumptions made about which materials are replaced by the recycled ones are very important. In this sense, more research is needed about what the recycled plastic may effectively substitute, in particular the mix of LDPE, LLDPE and PP. If this is used in the production of urban furniture, like it seems to be the case, the displaced virgin material should be wood and the analysis should be carried out accordingly.

Acknowledgment This research was supported by the Italian ministry of university and research (project "Environmental assessment of material and energy recovery from waste").

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